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LOFAR and APERTIF Surveys of the Radio Sky: Probing Shocks and Magnetic Fields in Galaxy Clusters

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Abstract. At very low frequencies, the new pan-European radio telescope LOFAR is opening the last unexplored window of the electromagnetic spectrum for astrophysical studies. The revolutionary APERTIF-phased arrays that are about to be installed on the Westerbork radio telescope (WSRT) will dramatically increase the survey speed for the

WSRT. Combined surveys with these two facilities will deeply chart the northern sky over almost two decades in radio frequency from ~ 15 up to 1400 MHz. Here we briefly describe some of the capabilities of these new facilities and what radio surveys are planned to study fundamental issues related to the formation and evolution of galaxies and clusters of galaxies. In the second part we briefly review some recent observational results directly showing that diffuse radio emission in clusters traces shocks due to cluster mergers. As these diffuse radio sources are relatively bright at low frequencies, LOFAR should be able to detect thousands of such sources up to the epoch of cluster formation. This will allow addressing many question about the origin and evolution of shocks and magnetic fields in clusters. At the end we briefly review some of the first and very preliminary LOFAR results on clusters.

Key words. Galaxies: clusters: general, intracluster medium; radio continuum: galaxies; radio telescopes.

1. Introduction

At low frequencies, the new pan-European radio telescope LOFAR is opening the last unexplored window of the electromagnetic spectrum for astrophysical studies. The revolutionary APERTIF-phased arrays that are about to be installed on the Westerbork radio telescope (WSRT) will dramatically increase the survey speed for the WSRT. The resulting vast area of new observational parameter space will be fully exploited for many studies directly related to the formation of massive black holes, galaxies and clusters. Particularly important are three research areas that are driving the design of several surveys that are planned to be carried out with these new facilities. These areas are: (i) forming massive galaxies at the epoch of reionization, (ii) magnetic fields and shocked hot gas associated with the first bound clusters of galaxies, and (iii) star formation processes in distant galaxies. Furthermore, a most exciting aspect of LOFAR is that its enormous instantaneous field of view coupled with its unprecedented sensitivity at low frequencies equips LOFAR for the discovery of new classes of rare extreme-spectrum sources.

In this contribution, we will first briefly describe LOFAR and APERTIF. For a more extended description of LOFAR we refer to the contribution of George Heald that extensively describes LOFAR and the way the data will be handled to form deep images at low frequencies. Second, we will discuss how the prime science drivers led to the definition of the planned continuum surveys with LOFAR and APERTIF. Third, we briefly review some of the work we have been carrying out to understand diffuse radio emission associated with merging clusters. We will mainly concentrate on some of the statistical results obtained for a partly new sample of relics showing correlations between their sizes, spectral indices and distances from the clusters centres. Reinout van Weeren has highlighted recent results for newly discovered individual relics, including the recently discovered spectacular double relics in the cluster CIZA J2252.8+5301 (van Weeren *et al.* 2010). Finally, a few preliminary results from LOFAR observations mainly related to clusters are briefly presented. These results show the enormous potential that LOFAR has for studying shocks and magnetic fields in clusters.

2. LOFAR

LOFAR, the Low Frequency Radio Array, is a pan-European radio telescope that is currently being commissioned. Its revolutionary design makes use of phased array technology. This replaces the traditional and expensive mechanical dishes by a combination of simple receivers and modern computing equipment. LOFAR has two types of antennas, one optimized for the 30–80 MHz range and one for the 110–240 MHz range. The antennas are grouped together in stations the size of soccer fields. The signals from the antennas will be digitized so that many beams on the sky can be formed. This makes LOFAR an extremely efficient instrument to survey large areas of sky. The Dutch part of the array will be finished in 2011 and will comprise 40 stations distributed over an area of diameter of 100 km. In addition, in 2011 eight stations in a number of European countries (Germany, UK, Sweden and France) are planned to be operational. Currently many functional elements of the LOFAR imaging system are in place. These elements include: (i) station beam formation, (ii) high speed data transport, (iii) software correlator to produce visibilities, (iv) calibration algorithms, and (v) wide field map making. Although a significant amount of both continued commissioning and technical research will be needed to obtain maps with theoretical noise levels, the maps that are currently produced already are the deepest ever at these low frequencies.

With its unique design, LOFAR will provide enormous improvements over previous facilities in the following three regions of parameter space:

- Very low frequencies, with 2–3 orders of magnitude improvement in both sensitivity and angular resolution. This is a mostly unexplored spectral region that is uniquely sensitive to ultra-steep spectrum $z > 6$ radio galaxies, diffuse emission from clusters and the oldest ‘fossil’ synchrotron electrons.
- Size of the instantaneous field-of-view, of many tens of square degrees. This will deliver a transformational increase in speed to survey the radio sky, crucially important for the quest for rare objects such as distant clusters, proto-clusters and $z > 6$ radio galaxies and rare transient phenomena.
- Low-frequency radio spectroscopy, enabling studies of red-shifted neutral hydrogen at the Epoch of Reionization.

The design of LOFAR is very versatile and has led to the development of 6 key science projects, related to cosmic rays, epoch of reionization, transients and pulsars, cosmic magnetism, the Sun, and extragalactic surveys. In this contribution, we will focus on LOFAR and APERTIF surveys to probe the extragalactic sky.

3. APERTIF

APERTIF, the new Phased Array Feed receiver system for the Westerbork Synthesis Radio Telescope (WSRT) will dramatically enlarge the instantaneous field-of-view of the WSRT (see Oosterloo *et al.* 2010 for a detailed description). This is done by replacing the current single Front-end Feeds with Phased Array Feeds (PAFS). Each of the PAFs consists of 121 Vivaldi elements and will detect the radiation field (in dual polarization) in the focal plane of each dish over an area of about one square meter. Because of this, many beams can be formed simultaneously for each dish

making it possible to image an area of about 8 sq. degree on the sky, which is an increase of about a factor 30 compared to the current WSRT. Its large 300 MHz bandwidth will not only cater to sensitive continuum imaging, but is also crucial for efficient HI and OH emission surveys and for studies of polarized emission from large areas.

4. Transformational radio surveys

4.1 LOFAR

The three fundamental areas of astrophysics that have driven the design of the planned LOFAR surveys are: (i) forming massive galaxies at the epoch of reionization, (ii) magnetic fields and shocked hot gas associated with the first bound clusters of galaxies, and (iii) star formation processes in distant galaxies. The areas, depths and frequencies of the surveys have been chosen so that they would contain: (i) 100 powerful radio galaxies close to or at the epoch of reionization, (ii) 100 radio halos at the epoch when the first massive bound galaxy clusters appeared, and (iii) 100 proto-clusters. The resulting survey parameters are based on estimates of luminosity functions for powerful radio galaxies by Wilman *et al.* (2008), for radio halos by Enßlin & Röttgering (2002) and Cassano *et al.* (2010), and for proto-clusters by Venemans *et al.* (2007). To achieve the goals of the LOFAR surveys, a three-tiered approach has been adopted (for details, see Röttgering *et al.* 2010). Tier-1 represents the all-sky survey at frequencies 15, 30, 60 and 120 MHz. Tier-2 are the medium deep surveys over 1000 sq. degrees at 30, 60, 120 and 200 MHz, while Tier-3 encompasses about 100 sq. degrees down to an extreme depth of 6 μ Jy rms at 150 MHz. The resulting depth versus frequency is given in Fig. 1. In addition, very deep data

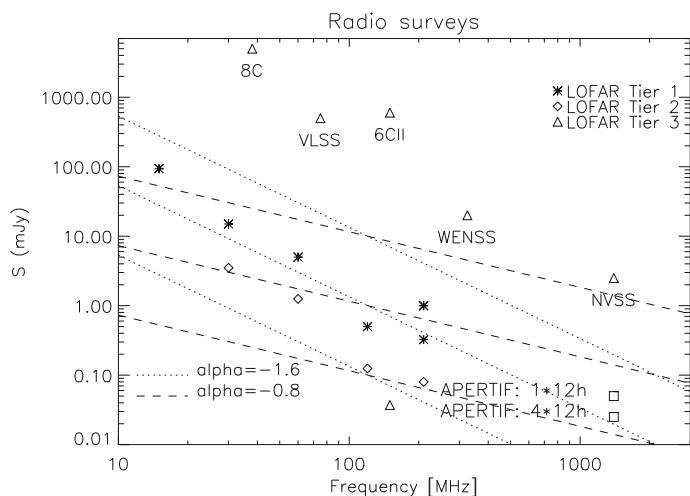


Figure 1. Flux limits (5 sigma) of the proposed LOFAR and APERTIF surveys compared to other existing radio surveys. The triangle represent existing surveys: HDF (VLA Richards *et al.* (2000); WSRT Garrett *et al.* (2000), WENSS, NVSS, 6C, VLSS and 8C. The lines represent different power-laws ($S \sim \nu^\alpha$, with $\alpha = -1.6$ and -0.8) to illustrate how, depending on the spectral indices of the sources, the LOFAR surveys will compare to other surveys.

will be taken on a selected sample of 60 nearby clusters. Another important motivation of LOFAR is to provide the entire international astronomical community with unique surveys of the radio sky that have a long-lasting legacy value for a broad range of astrophysical research. The international LOFAR survey team has identified a range of fundamental astrophysical research topics on which LOFAR surveys will have an important impact. These topics include (i) the formation and evolution of large-scale structure of the Universe, (ii) the physics of the origin, evolution and end-stages of radio sources, (iii) the magnetic field and interstellar medium in nearby galaxies, and (iv) galactic sources such as supernova remnants, HII regions, exoplanets and pulsars.

4.2 WODAN

The extremely large field of view of APERTIF would enable the WODAN (Westerbork Observations of the Deep APERTIF Northern-Sky) project. This project aims to chart the entire accessible northern sky at 1400 MHz down to $10 \mu\text{Jy}$ rms and about 1000 deg^2 down to $5 \mu\text{Jy}$. WODAN will be an important compliment to the EMU (Evolutionary Map of the Universe) project. EMU will use the phased-array feed (PAF) mounted on the Australian SKA Pathfinder (ASKAP, Deboer *et al.* 2009) to chart the entire sky south of $\delta = 30^\circ$ to a similar depth as WODAN. For a detailed description of EMU, we will refer to Ray Norris (2011).

WODAN and EMU have an enormous synergy with the LOFAR surveys: virtually all the 5×10^7 radio sources from the LOFAR all-sky surveys will have their flux density at 1400 MHz measured. It will yield radio data for all radio-loud AGN, and most luminous starbursts up to $z = 2$. The resulting densely populated radio color-color diagrams will be a powerful tool to spectrally discriminate between very rare radio sources with extreme radio spectra such as diffuse emission from clusters and very distant radio galaxies. For nearby resolved sources it will instantly yield spectral index and spectral curvature maps, a very rich source of information to constrain many physical parameters. As the combined surveys will cover the entire sky, measurements of the Integrated Sachs–Wolfe effect, galaxy auto-correlation functions and cosmic magnification will significantly tighten cosmological model parameters (Raccanelli *et al.* 2011).

5. LOFAR and diffuse radio emission from clusters of galaxies

Clusters of galaxies are large ensembles of hundreds of galaxies embedded in hot gas and held together by gravity. Besides the hot thermal gas observed in X-rays, the intra-cluster-medium (ICM) contains relativistic electrons ($E \approx \text{GeV}$) and magnetic fields ($1\text{--}10 \mu\text{G}$), which have been detected via synchrotron emission in the radio band. LOFAR is uniquely suited to probe these synchrotron emitting regions and will address many questions related to the large-scale magnetic fields and relativistic particles mixed with the thermal ICM. These questions include: What are the strengths and topologies of the magnetic fields? When and how were the first magnetic fields generated? How were magnetic fields subsequently amplified and maintained?

Furthermore, diffuse radio sources in galaxy clusters are likely to be direct signatures of huge shock waves caused by massive cluster mergers. These shocks have a crucial impact on the energetics and detailed temperature distribution of the cluster gas. LOFAR observations are therefore very relevant for studies of the evolution of the energy content of both the thermal and non-thermal gas in the cluster. Some of the most prominent nearby clusters of galaxies host such diffuse synchrotron emitting radio sources. Classical examples of spectacularly large (~ 1 Mpc) diffuse cluster emission have been found for the Coma cluster, Abell 2256 and Abell 3667. The properties of the associated clusters are extreme: they are very X-ray luminous, have high temperatures ($kT > 7$ keV), large masses ($> 10^{15} M_{\odot}$), and high galaxy velocity dispersions. The overall properties are indicative of the violent merging of sub-clusters, an important process in the assembly of massive clusters. Diffuse radio emission associated with clusters of galaxies has been classified into three groups: relics, halos and phoenixes (e.g. Giovannini & Feretti 2004).

Cluster relics are large elongated diffuse structures at the periphery of clusters. Recently we have discovered a spectacularly long and narrow relic with a size of $2.0 \text{ Mpc} \times 50 \text{ kpc}$, located at a distance of 1 Mpc from the centre of the merging cluster CIZA J2242.8+5301 (van Weeren *et al.* 2010). The relic displays highly aligned magnetic fields and a strong spectral index gradient due to cooling of the synchrotron emitting particles in the post shock region. We have argued that these observations provide conclusive evidence that shocks in merging clusters produce extremely energetic cosmic rays. Detailed modelling of the morphology, polarization properties and variations of the radio spectrum, allowed us to determine the strength of the magnetic field ($5 \mu\text{G}$) and the Mach number ($4.6^{+1.3}_{-0.9}$) of the shock. Our numerical simulations indicated that the impact parameter of the cluster collision was about zero and the mass ratio of the colliding clusters was roughly 2 : 1 (van Weeren *et al.* in prep.).

Cluster radio halos are located at the centres of clusters, their diffuse morphologies following that of the X-ray emission. The origin of the halos is not understood. Especially their enormous ~ 1 Mpc sizes pose problems. The radiative lifetimes of the synchrotron emitting electrons are so short that the electrons need to have been accelerated to relativistic speeds close to the place where they radiate. Although many explanations have been put forward, a currently favoured one is that turbulence due to cluster mergers is capable of accelerating electrons to relativistic speeds (e.g. Brunetti *et al.* 2001). Alternatively, relative electrons could be produced when relativistic protons from AGNs in the cluster collide with thermal protons within the cluster gas (Dennison 1980). A second important issue relates to the origin of the magnetic fields (e.g. Dolag 2006). Are they primordial in origin and have turbulent processes subsequently amplifying the fields? Or have outflows from active galaxies or starburst galaxies transported magnetic fields into the inter-galactic medium?

Radio phoenixes are suggested to be due to shocks in the cluster gas that would adiabatically compress old radio plasma ejected by former active galaxies. The resulting diffuse objects would have an extremely steep radio spectrum making them relatively bright at low radio frequencies (Enßlin and Gopal-Krishna 2001). Simply considering the timescales related to the AGN activity, synchrotron losses, and the presence of shocks we recently argued that such sources could determine the general appearance of clusters in low frequency LOFAR maps (van Weeren *et al.* 2009a).

Because these radio sources associated with cluster wide shocks are diffuse, have low luminosities and steep radio spectra, they are difficult to detect with conventional radio observatories, such as Westerbork. As a result there are only about 50 cluster radio sources currently known. Due to its extreme sensitivity at low radio frequencies, LOFAR will be the break-through instrument for this field of research (Cassano *et al.* 2010). For the first time, the occurrence and characteristics of diffuse cluster radio sources will be measured as a function of cluster properties up to the epoch at which the first massive clusters assembled ($z \sim 1$). This will directly show the effects of shock waves on the evolution of the cluster gas and magnetic fields, and test predictions that cluster merging is rampant at high red-shift. Detailed LOFAR maps of rotation measures, polarization properties and radio spectra of nearby halos will distinguish between the various physical models for the origin of the diffuse radio emission. It also will probe radio AGN activity over long time scales, important for studies of the radio feedback processes in clusters. With the LOFAR observations, we will address the following questions:

- What are the properties of the cluster-wide shocks (rate of occurrence, volume filling, geometry, Mach numbers)? How do they accelerate particles?
- What are the characteristics of the magnetic fields (strength, topology)? And how do these relate to models of the origin of the fields?
- What is the total energy input into the cluster medium by radio loud AGN?
- What are the properties of the merging clusters (mass ratios, impact parameters) as can be directly deduced by the relic morphologies?
- How do the properties of merging clusters evolve over cosmic time?

6. Towards a sample of relics, a prelude to LOFAR

As discussed, detailed radio observations of individual relics clearly suggest that relics originate in shocks induced by merging clusters. This scenario can be further tested by studying larger samples of relics. From GMRT, WSRT and VLA observations of a sample of diffuse radio sources from the 74 MHz VLSS survey with spectral indices $\alpha < -1.7$, 5 new relics were discovered. A comparison of the NVSS and WENSS radio catalogues with the ROSAT all-sky catalogue, 5 additional relics were found. Combined with 17 known relics from the literature, the resulting sample was large enough for a statistical study. For details we refer to van Weeren *et al.* (2009b). For this sample, we found that larger relics are mostly located in the cluster periphery, while smaller relics are found closer to the cluster center. We also discovered an anti-correlation between the steepness of the spectral index and the physical size of the relics. A likely explanation for these two correlations is that the larger shock waves occur mainly in lower-density regions. The larger shocks then have larger Mach numbers translating into flatter radio spectra. As larger relics are also more luminous, this then also explains that within this sample the more luminous radio relics have flatter spectral indices. Finally, there is a tendency for the steep spectrum relics to show more spectral curvature. This would provide evidence for spectral ageing due to inverse Compton and/or synchrotron losses. We note however that some of the smallest relics might be due to the compression of fossil AGN radio plasma. Their very steep and curved spectrum sources are also consistent with this scenario.

6.1 LOFAR and cluster observations: The rich cluster of galaxies Abell 2256

Abell 2256 is a rich X-ray cluster at $z = 0.058$ that has undergone a merging event estimated to have happened 0.3 Gyr ago (e.g. Miller *et al.* 2003). Apart from 9 tailed sources, it rather exceptionally contains three classes of diffuse cluster radio sources: relics, halos and phoenixes. The northern relics have been discovered a long time ago (Bridle and Fomalont 1976) and were studied in detail by Clarke and Enßlin (2006). They also clearly showed that A2256 possesses a central halo with a luminosity following the X-ray – radio halo luminosity relation (Liang *et al.* 2000). In very deep 325 MHz GMRT radio maps, van Weeren *et al.* (2009a) recently discovered three diffuse elongated radio sources with extremely steep spectral indices located about 1 Mpc from the cluster center. These properties indicate that these objects can be classified as phoenixes.

As A2256 is one of the most luminous radio emitting clusters showing so many intriguing characteristics, it was one of the prime candidates to be observed during early commissioning of LOFAR (see also Röttgering *et al.* 2010; Heald *et al.* 2010). It was observed in the HBA band in May 2010 for about 8 hours. The data were taken with 10 core stations and 5 remote stations and the observed frequencies ranged from 115 to 165 MHz. An image from 18 subbands covering a total of 4 MHz of bandwidth around 135 MHz was made (see Fig. 2). The resolution of the image is 31×19 arcsec and the noise is ~ 5 mJy/beam. So far, the deepest images at low

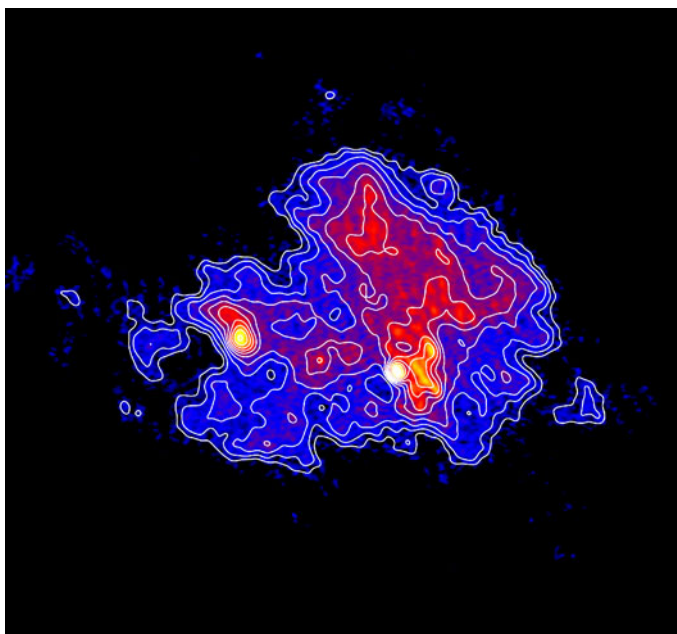


Figure 2. A 135-MHz LOFAR image of the rich X-ray cluster of galaxies A2256 at $z = 0.058$. The image has been made from data that were taken with 10 core stations and 5 remote stations. Only 4 MHz bandwidth out of a total 48 MHz was used during reduction. The resolution of the image is about 31×19 arcsec and the noise is ~ 5 mJy/beam. Beside several tailed galaxies and the relic structures, the image shows for the first time a spatially resolved central halo of A2256 at low frequencies.

frequencies have been obtained with the GMRT at 150 MHz (Intema 2009; Intema *et al.* submitted; Kale and Dwarakanath 2010). The GMRT image clearly shows the relic and several of the head–tail galaxies that are also visible on the LOFAR image. The GMRT image recovers the central part of the halo emission. With LOFAR’s very sensitive central core, the full extent of the halo is visible, showing LOFAR’s power to study diffuse steep spectrum emission from clusters. Next steps in improving this image are reducing the data from all the 256 sub-bands, and the application of more sophisticated data reduction algorithms. These include proper wide-field imaging taking the varying station beams into account, iteration of self-calibration/peeling loops, and removal of ionospheric corrections following the ‘SPAM’ method (Intema *et al.* 2009). Finally, recently we have observed A2256 in the low band and produced images at 20, 30 and 49 MHz. A spectral map from a combination of 49 MHz and the 350-MHz WSRT data (Brentjens *et al.* 2008) very nicely spatially resolved the extremely steep spectrum central radio halo from the flatter spectrum northern relics. We also recently obtained data on Coma A and A2255. The commissioning team is working very hard to obtain excellent images.

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